Technology to Market: Cost-Benefit Analysis of AMPED Technologies

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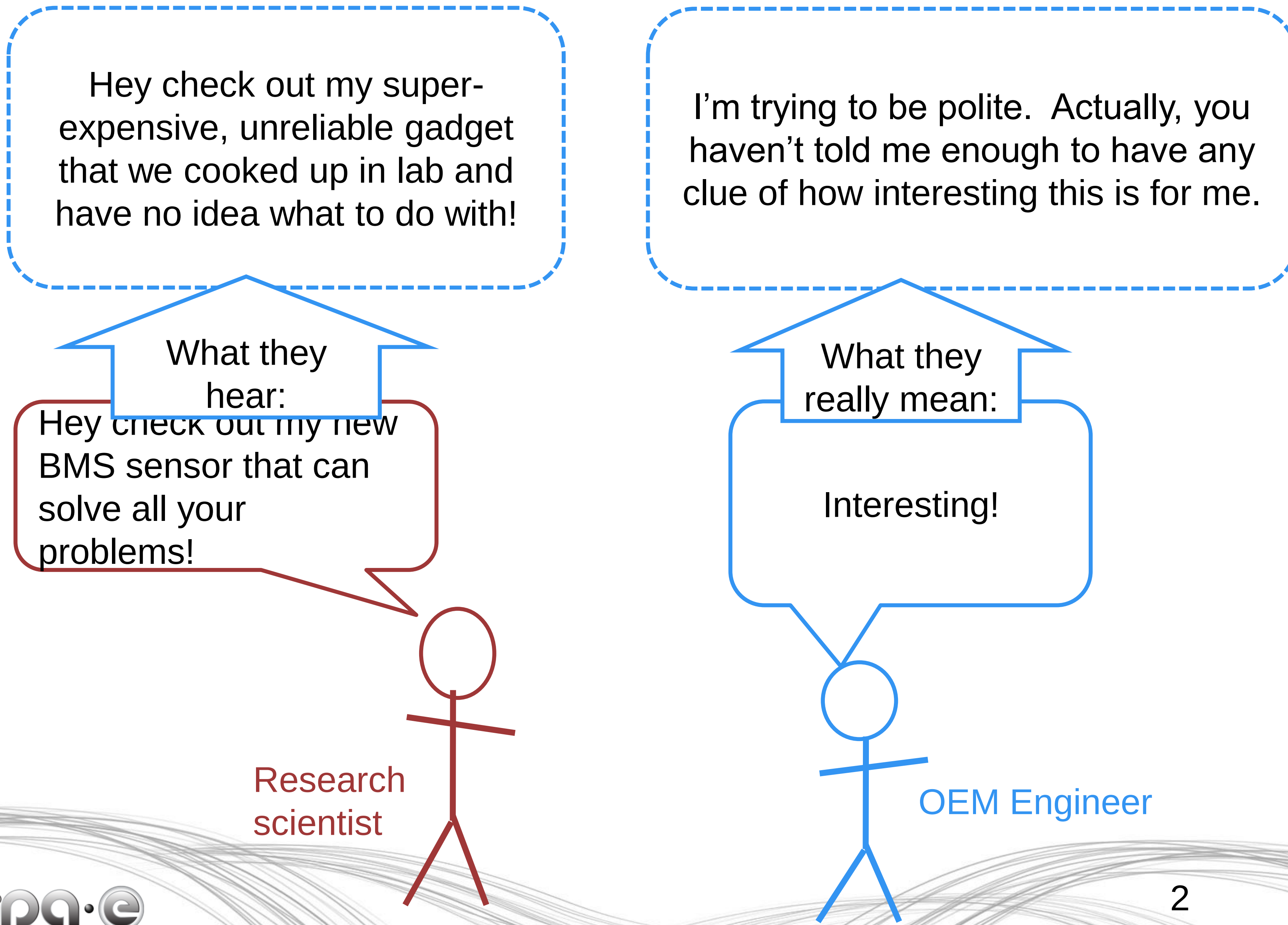
9 January 2013

Getting past the Standard Interaction



Getting past the Standard Interaction

Working toward shared goals

How do we go from
cool technology to scalable technology?

Lab researcher

OEM R&D Engineer

Innovation

People creating value through the implementation of new ideas

» Herman D'hooge, Intel

» Innovation Network

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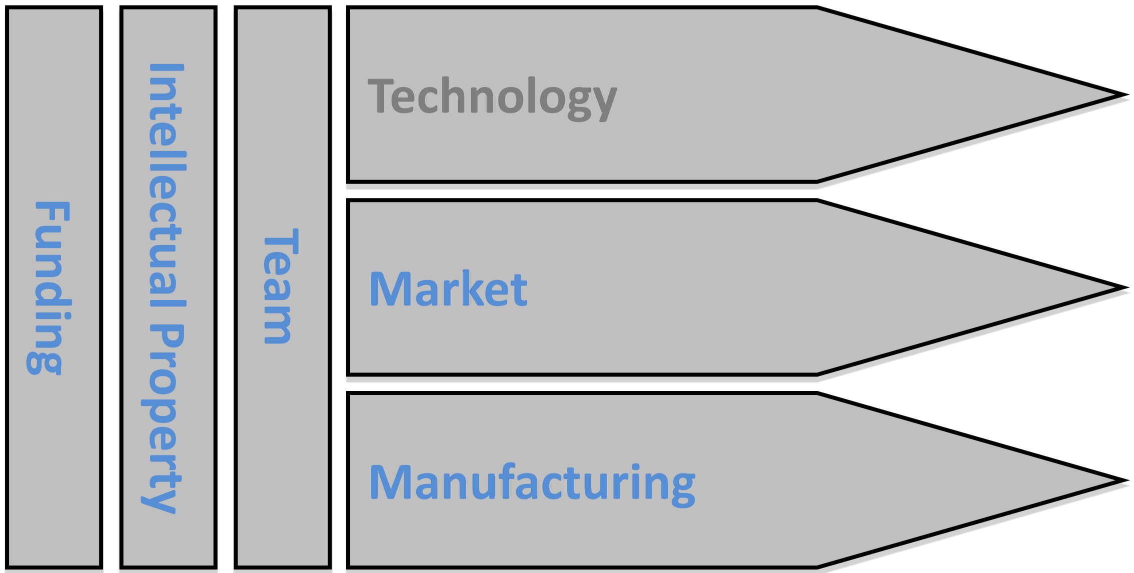
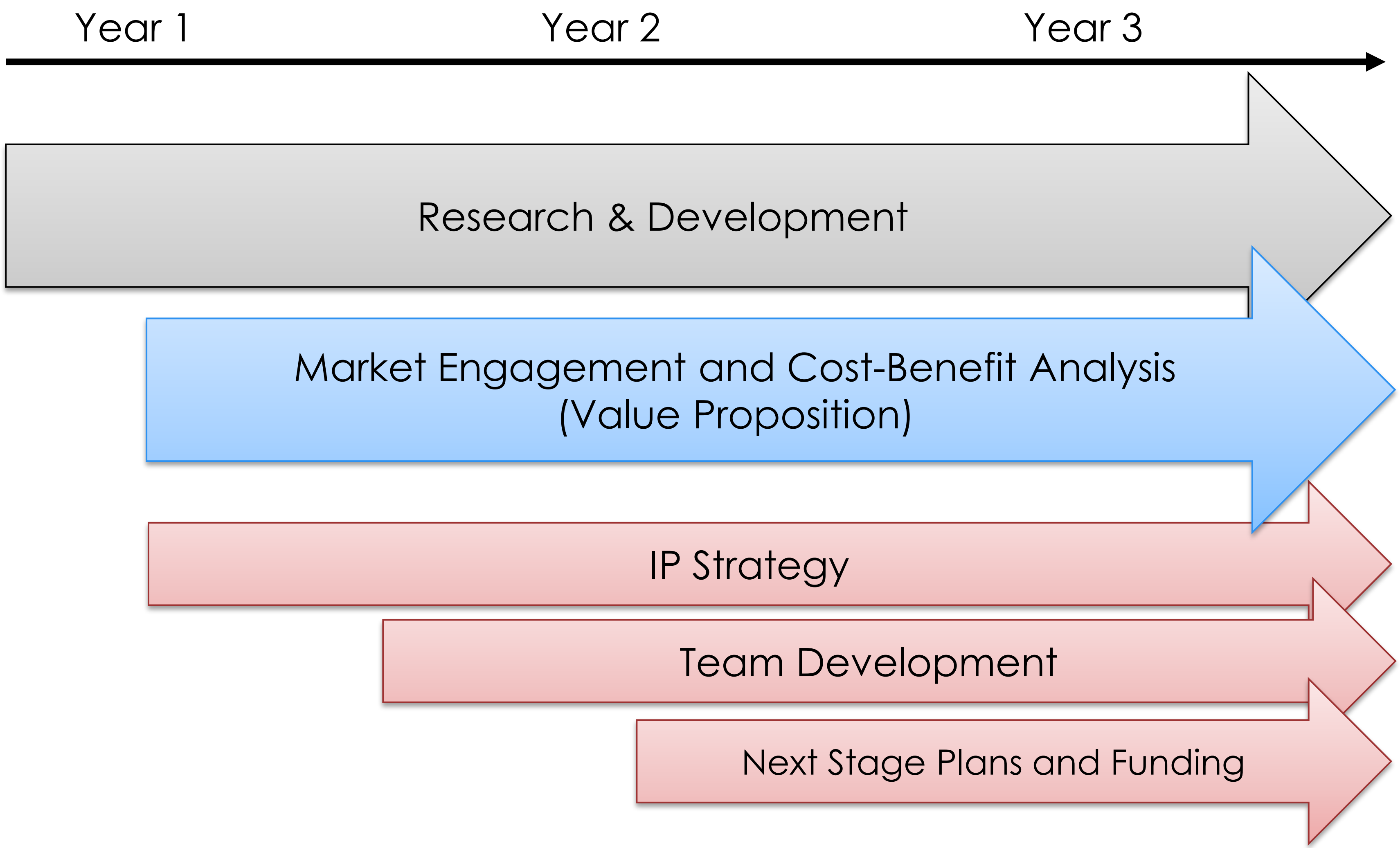
Technology-to-Market



Key Activities for AMPED Teams



The BMS Design Space

Knobs

Outputs

Externalities

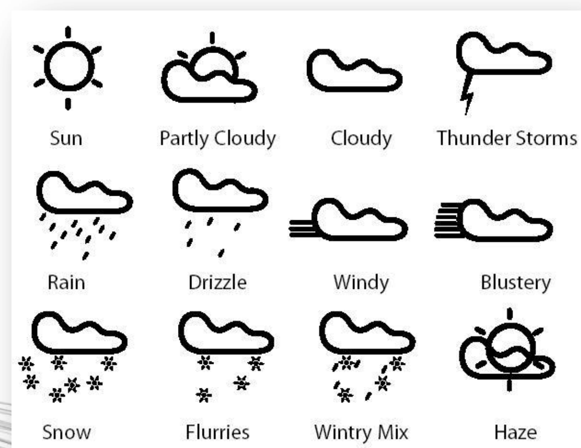


Image Sources:
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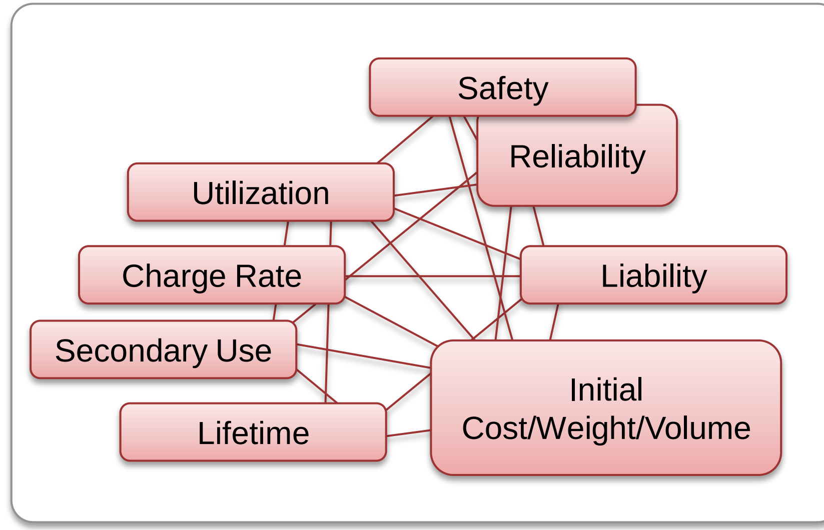
http://www.plmsdevelopments.com/images_if/gauges.jpg
http://www.linguistics.pitt.edu/henderson/Henderson%20Photos-2/Lab/control-knobs.jpg

The BMS Design Space

Knobs

- Charge profile
- SOC Window
- Drive mode
- Controls
- Diagnostics
- Therm. Management
- Pack Size
- Cell equalization
- Cell Format
- Cell Chem.
- Circuit Arch.

Outputs



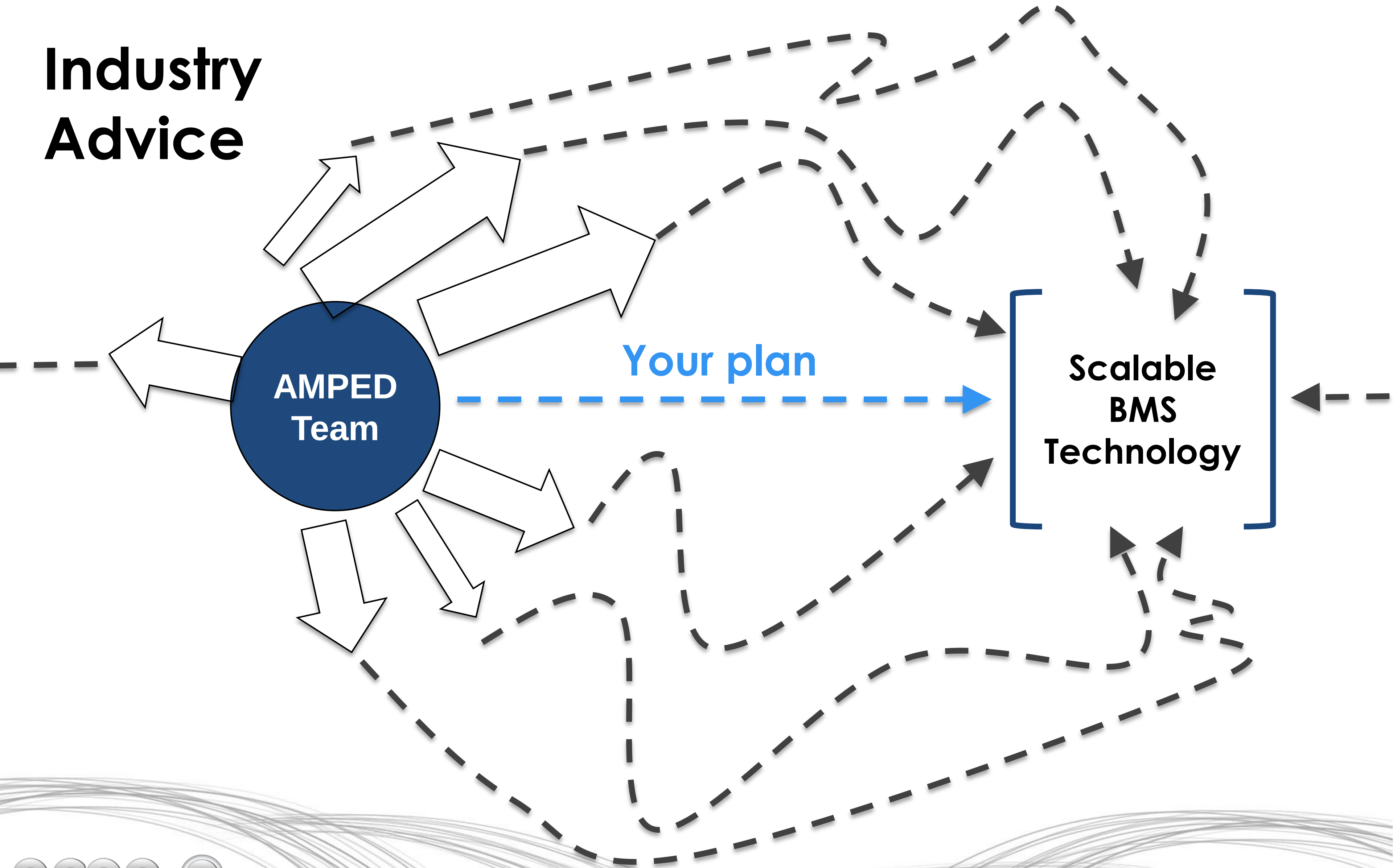
Externalities

- Operating Temp.
- Drive Profile
- Cell mfg errors
- Collisions
- Consumer demand
- Regulatory

The BMS Design Space

Image Source: http://cdnfiles.hdrcreme.com/32115/medium/knobs-switches.jpg?1318063005

Developing Scalable BMS Technologies



Developing Scalable BMS Technologies

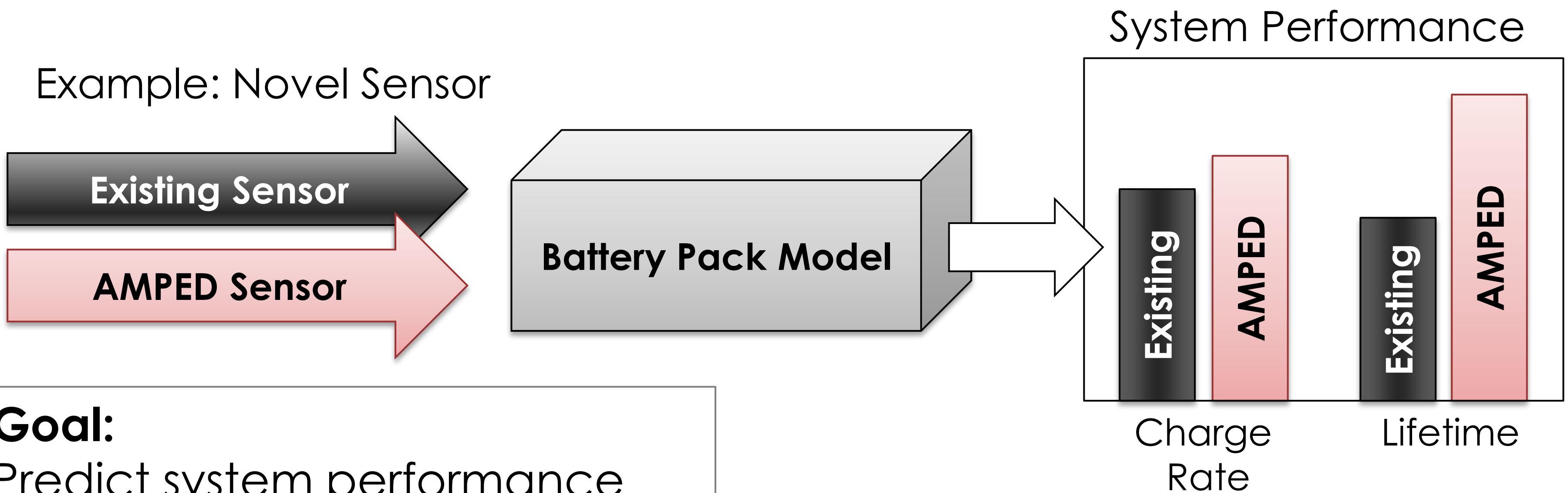
Component Level Innovation → **System Level Technical Performance** → Customer Value Proposition

Cost Analysis

Scalable BMS Technology

Goal:
Predict system performance with State-of-Art Component vs AMPED Component

Predicting System Performance Improvement



Goal:
Predict system performance with State-of-Art Component vs AMPED Component

Challenge #1: Vast Scope of Information Needed

Example: Novel Sensor

Existing Component Performance Data

Required Info:
- Accuracy
- Spatial resolution
- Time resolution
- Durability
- Size

Resources:
- Spec Sheets
- Interviews
- Tear-down reports

Challenges
- Proprietary
- Highly detailed

Battery Pack Model

Required Info:
- No. of sensors
- Sampling rate
- Controls scheme
- Power topology
- Thermal Management

Resources:
- Interviews
- Tear-down reports

Challenges
- Proprietary
- Inaccessible

Modeling Results

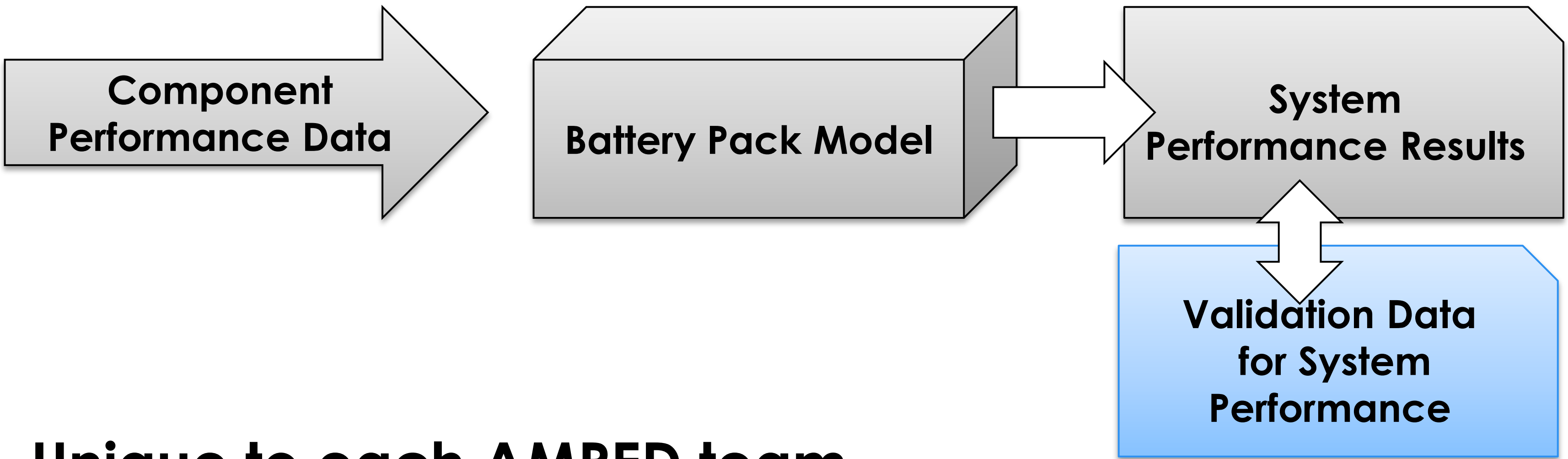
Validation Data for System Performance

Required Info:
- Vehicle range
- Charge rate
- Capacity fade
- Safety

Resources:
- Internal pack performance reports

Challenges
- Proprietary
- Highly coupled outcomes

Challenge #2: Defining the System to Model

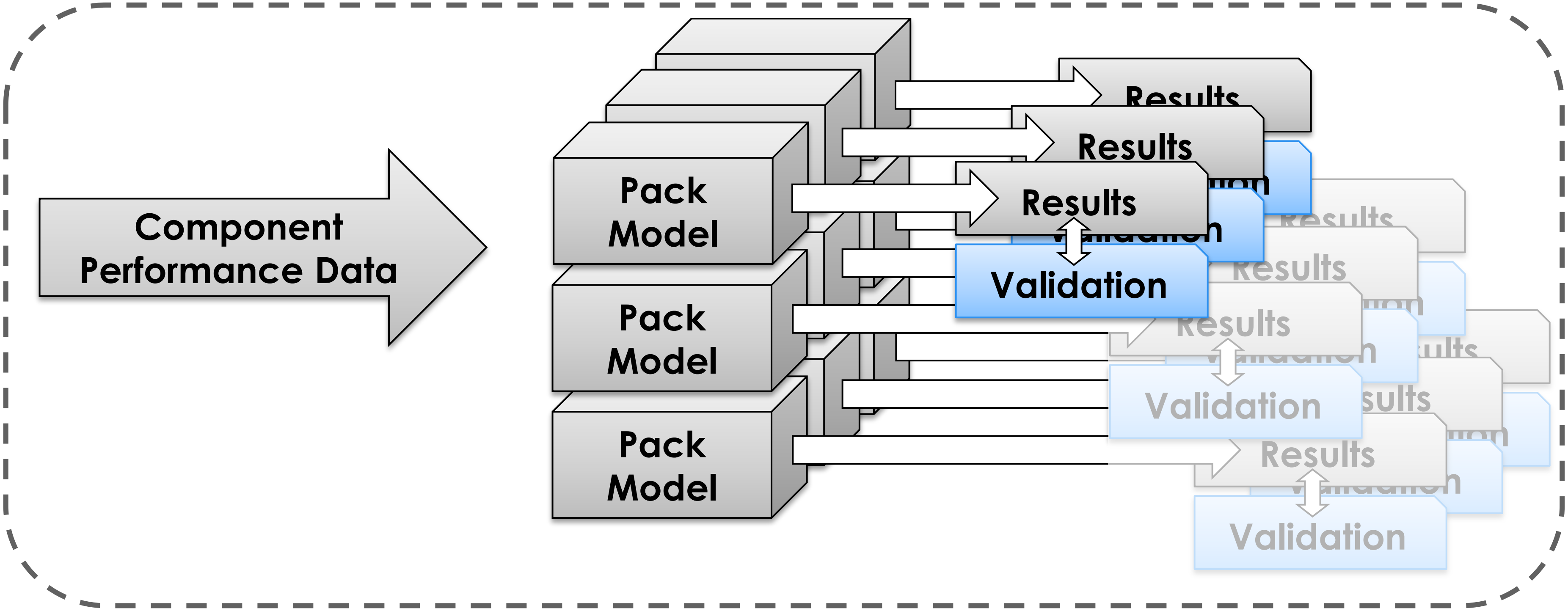


Unique to each AMPED team

System model subject to change

- Different vehicle types: HEV, PHEV, AEV
- Different battery designs
- New technologies

Challenge #2: Defining the System to Model



Determining system-level performance is a **multivariate, multidisciplinary optimization problem**

Practical Approaches to Determining System-Level Performance Improvements

Approach #1: Seek Expert Advice

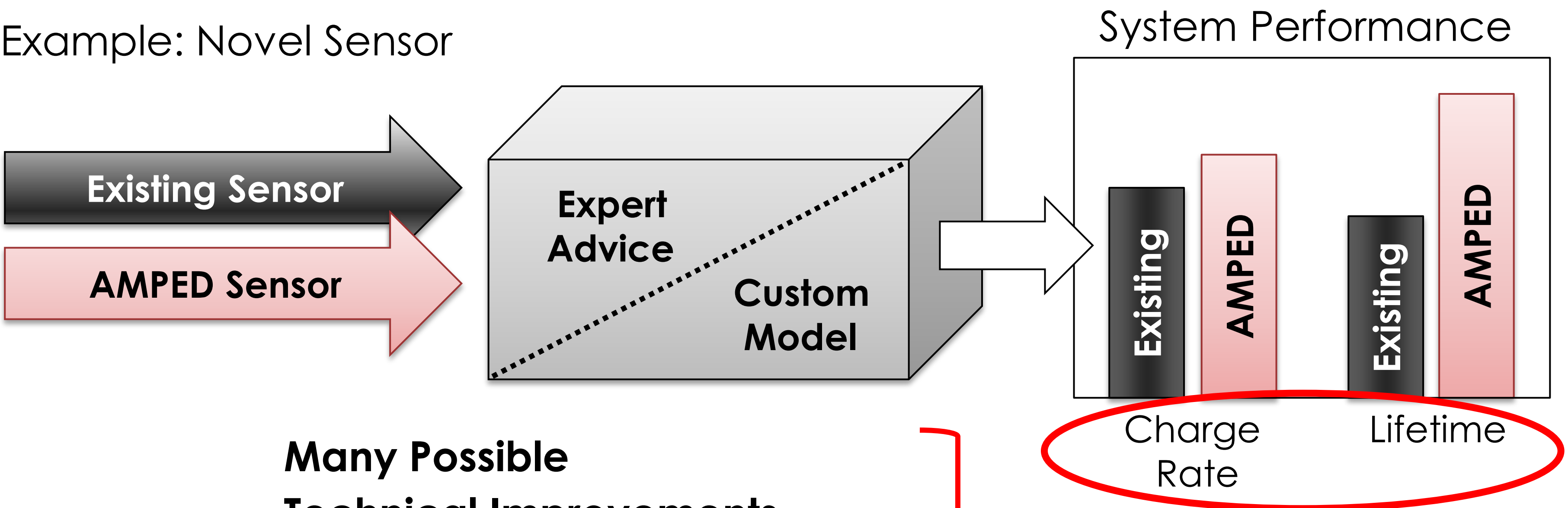
Benefits	Drawbacks
• Expert intuition serves to synthesize complex problem. • Details can remain proprietary while conclusions are shared. • Experts are often potential investors and future customers.	• Expert opinions vary dramatically. • Disruptive technologies are impossible foresee. • Motives may vary.

Approach #2: Build a Custom Battery Pack Model

Benefits	Drawbacks
• Assumptions are clear. • May break conventional wisdom. • Existing models provide a launch point.	• Assumptions may be wrong. • Time-intensive. • Miss the forest for the trees. • Quality input data is elusive.

Many Possible Outcomes to Compare

Example: Novel Sensor

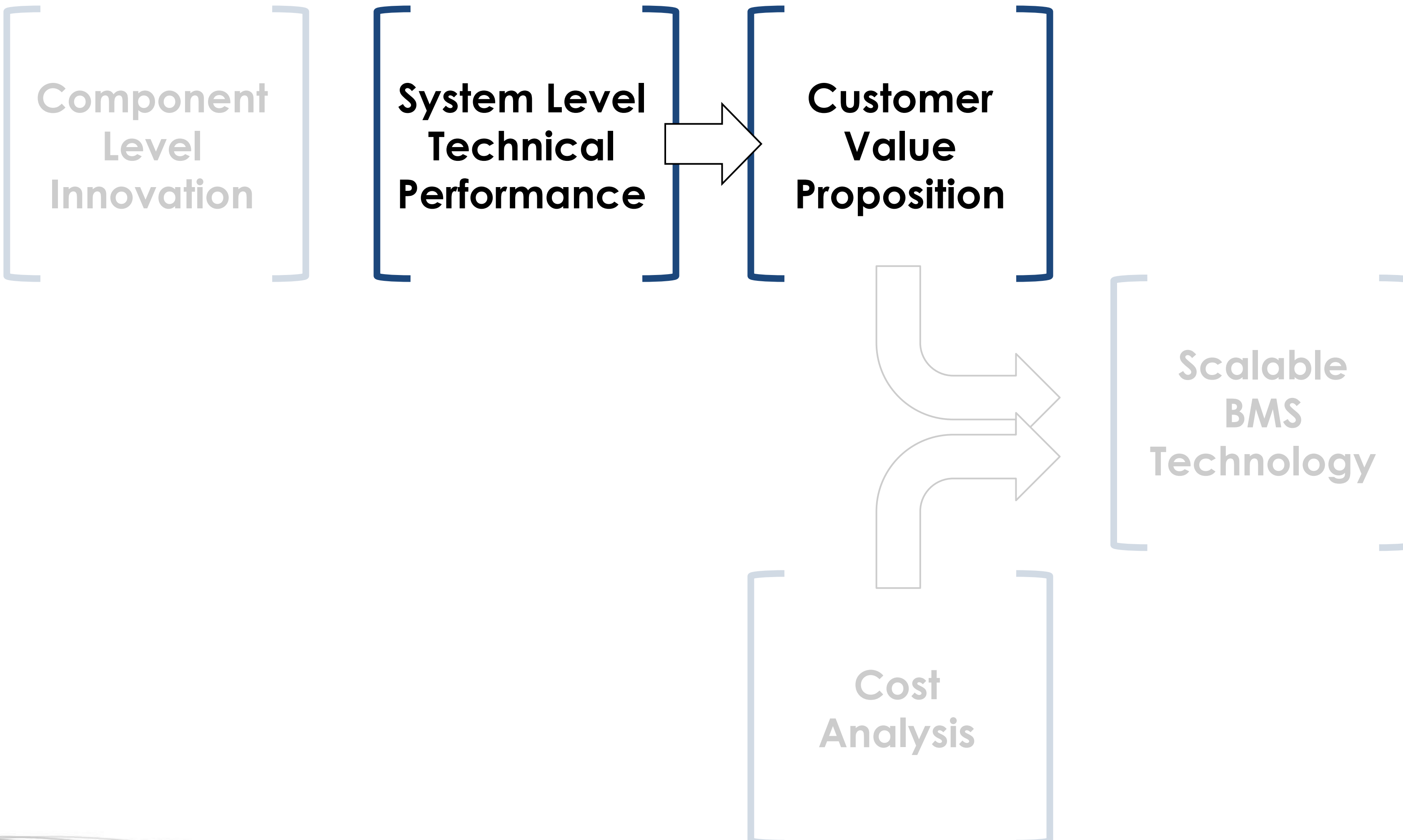


Many Possible Technical Improvements

Extended range
Increased charge rate
Reduced initial pack size (cells)
Reduced non-cell components
Increased lifetime
Improved pack safety
Improved reliability
Improved life estimation

How to determine which system level performance improvements to pursue?

Developing Scalable BMS Technologies



Reaching the Customer

New
AMPED Tech

System Performance Improvements

Extended range
Increased charge rate
Reduced initial pack size (cells)
Reduced non-cell components
Improved pack safety
Full cell yield utilization
Improved reliability
Improve

Value Propositions

ers

Ms
Tier 1 Suppliers
Charge stations
Fleet operators
Cell manufacturers
Grid storage companies

Definition:
A quantifiable benefit offered to a customer.

Reaching the Customer

New AMPED Tech

System Performance Improvements

Extended range
Increased charge rate
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Full cell yield utilization
Improved reliability
Improved life estimation

Value Propositions

Vehicle cost savings
Increased vehicle adoption
Regulation compliance
Increased charger use
Fleet capacity factor
Increased cell value
Decreased warranty cost

Possible Customers

Automotive OEMs
Tier 1 Suppliers
Charge stations
Fleet operators
Cell manufacturers
Grid storage companies

Framework for Assessing Value Propositions

Framework provides:

- Methodical breakdown of value
- Techniques for quantifying value
- Targeted references

System Performance Improvements

Extended range
Increased charge rate
Reduced initial pack size (cells)
Reduced non-cell components
Improved pack safety
Full cell yield utilization
Improved reliability
Improved warranty estimation

		Value Proposition	*Potential Customer*
Reduced Initial Pack Size (cells)	[illegible]	Vehicle Cost Savings	OEMs, Tier 1s
	Fewer cells	Vehicle Cost Savings	OEMs, Tier 1s
	Improved Handling	Vehicle Adoption	OEMs
	Increased Trunksize	Vehicle Adoption	OEMs

Value Proposition: Reduced Initial Pack Size (Cells)

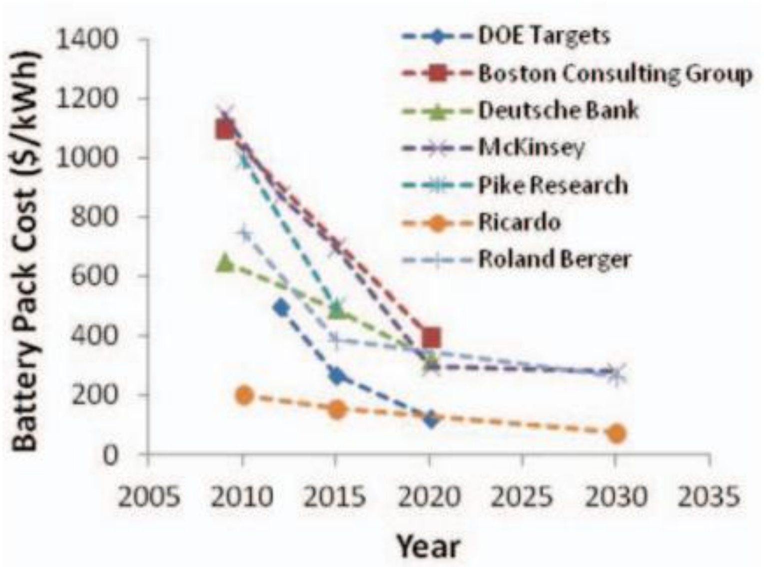
Technical Improvement	Intermediate Benefit	Value Proposition	Potential Customer
Reduced Initial Pack Size (cells)	Lightweighting	Vehicle Cost Savings	OEMs, Tier 1s
	Fewer cells	Vehicle Cost Savings	OEMs, Tier 1s
	Improved Handling	Vehicle Adoption	OEMs
	Increased Trunksize	Vehicle Adoption	OEMs

- Varied cost savings
  - Decreased Bill of Materials (BOM)
  - Reduced powertrain requirements
  - Secondary mass savings
- Very active research area for automotive industry. All major manufacturers have value estimates for lightweighting.
- Value: $3-4/lb (VTP truck study 2012)
- Lightweighting cost models
  - Bjelkengren Thesis, MIT, 2006 (Overview and Secondary Mass Savings)
  - Alexandra Frangi, MIT, 2001 (Tech. Cost Modeling (TCM))

Value Proposition: Reduced Initial Pack Size (Cells)

Technical Improvement	Intermediate Benefit	*Value Proposition*	*Potential Customer*
Reduced Initial Pack Size (cells)	Lightweighting	Vehicle Cost Savings	OEMs, Tier 1s
	Fewer cells	Vehicle Cost Savings	OEMs, Tier 1s
	Improved Handling	Vehicle Adoption	OEMs
	Increased Trunksize	Vehicle Adoption	OEMs

- Cell Costs
  - Approximate: $650/kWh (usable)
  - Projected to decrease:
    ~150-400 $/kWh by 2020)
- References
  - DOE
  - Private sector



J. Neubauer, A. Pesaran, B. Williams, M. Ferry, J. Eyer

Value Proposition: Reduced Initial Pack Size (Cells)

Technical Improvement	Intermediate Benefit	*Value Proposition*	*Potential Customer*
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	Improved Handling	Vehicle Adoption	OEMs
	Increased Trunksize	Vehicle Adoption	OEMs

- Handling
  - Difficult to quantify.
  - Significant interest in improved handling in performance vehicles.
  - Battery results in low center of gravity. Nissan Leaf achieved nearly 1g acceleration with extensive after-market tweak.
- Trunksize
  - Secondary benefit, more relevant to late-adopters.
  - Brownstone 2000 looked at luggage space. No other known studies.

Value Proposition Framework Available

Technical Improvement	**Intermediate Benefit**	*Value Proposition*	*Potential Customer*
Reduced Initial Pack Size (cells)	Lightweighting	Vehicle Cost Savings	OEMs, Tier 1s
	Fewer cells	Vehicle Cost Savings	OEMs, Tier 1s
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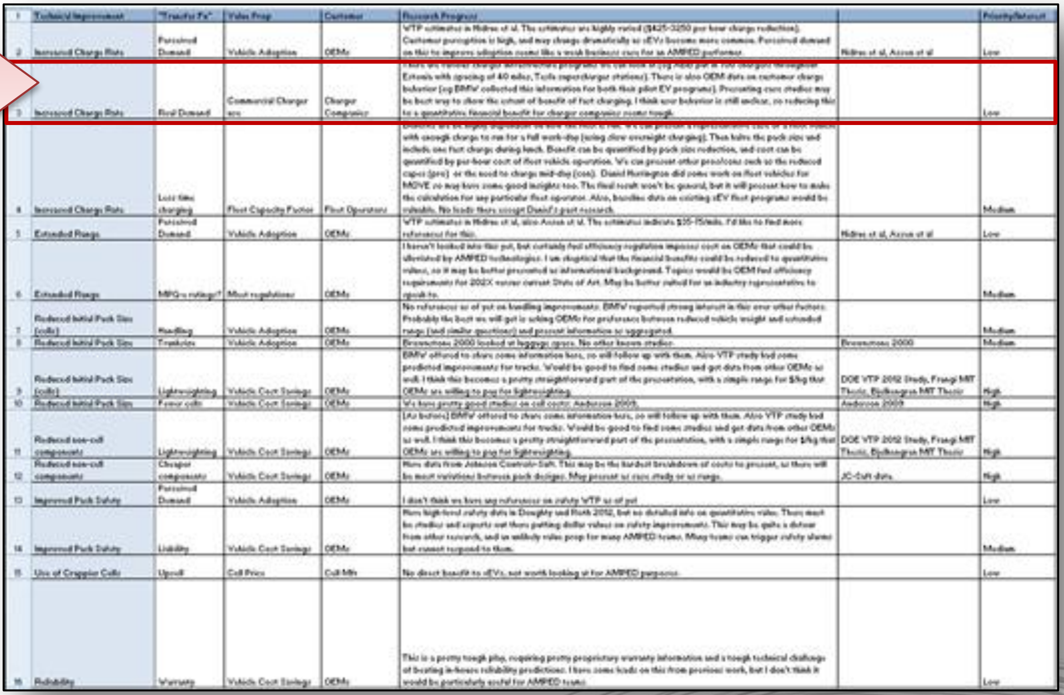
	Increased Trunksize	Vehicle Adoption	OEMs



Spreadsheet of value propositions:

- Full list of value propositions
- Techniques for quantification
- References

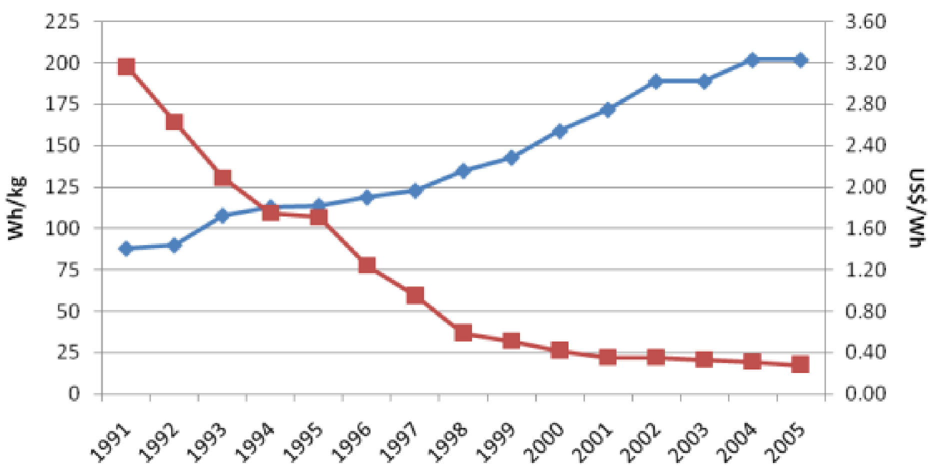
Available to all Attendees

Living document… *Input welcome!*

Effects of Industry Trends on Value Analysis

Trend

Increasing cell energy density



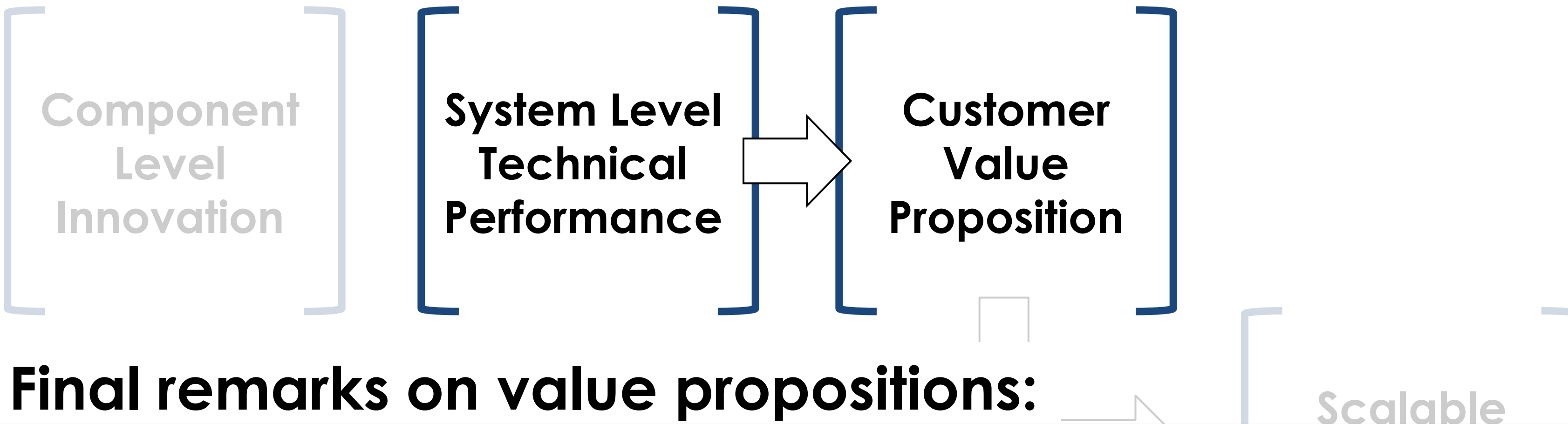
Li-Ion Pricing (Red) and Energy Density (Blue)
Source: Buchman 2005, from Anderson 2009

Potential Implications

- Less value of pack-lightweighting
- More value to cell enhancement
- More value to cell safety
- More relative value in reducing non-cell components

Understanding how value propositions are calculated allows you to integrate trends.

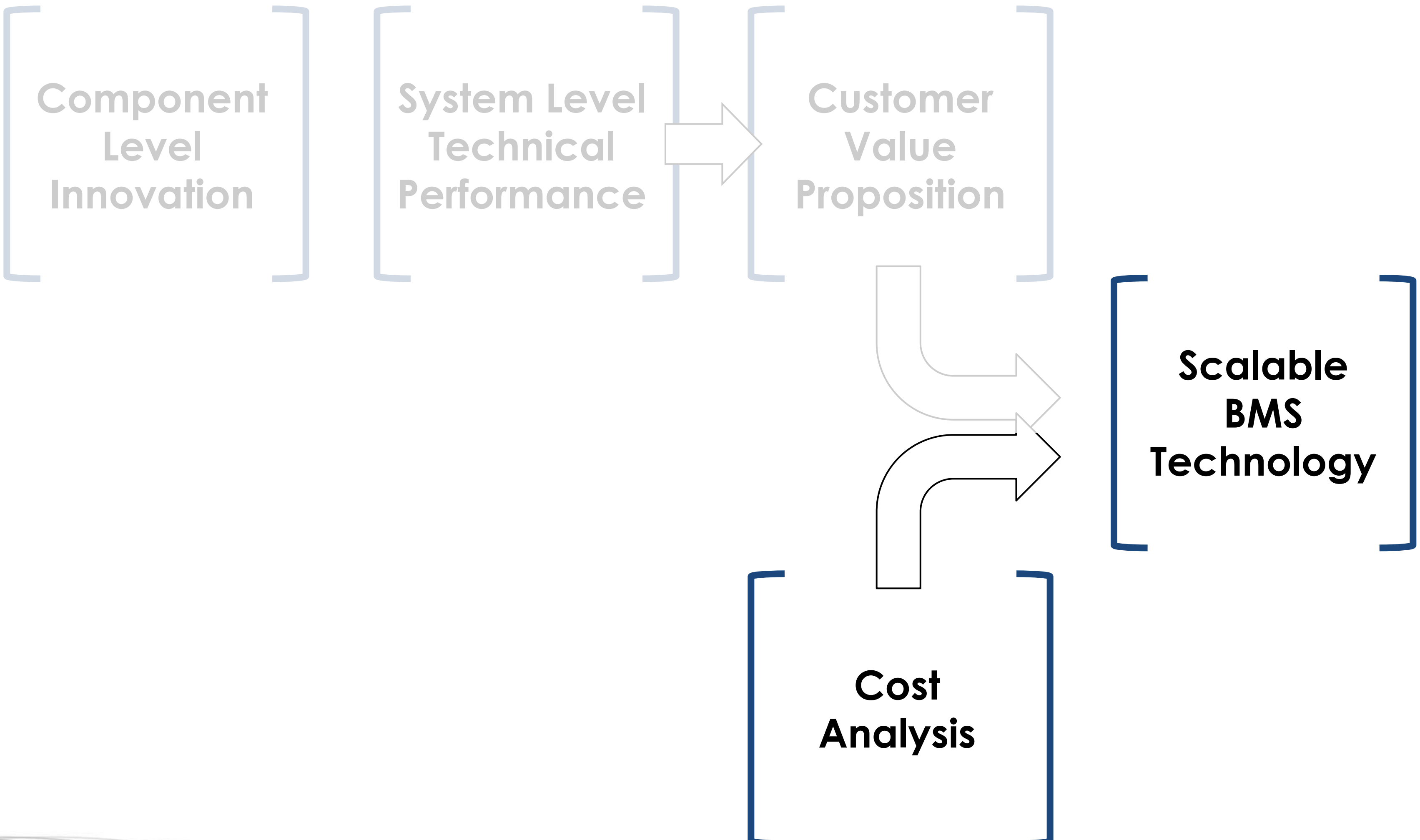
Developing Scalable BMS Technologies



Final remarks on value propositions:

- System-level performance improvements ***alone*** will not yield a scalable technology.
- Value proposition framework is only a tool for orientation.
- You won't know actual value until you have actual customers.
- Each customer has its own lens.
- Value propositions are your "technology budget".

Developing Scalable BMS Technologies



Cost-Analysis for AMPED Technologies

- Expectations
  - Customers do *not* expect a perfect cost model
  - Customers do need reason to believe value outweigh costs

- A phased approach

Technology Development

Early R&D → Prototyping → Demonstration

Cost-Analysis

Cost-aware design → Preliminary Cost Model → Detailed Cost Model

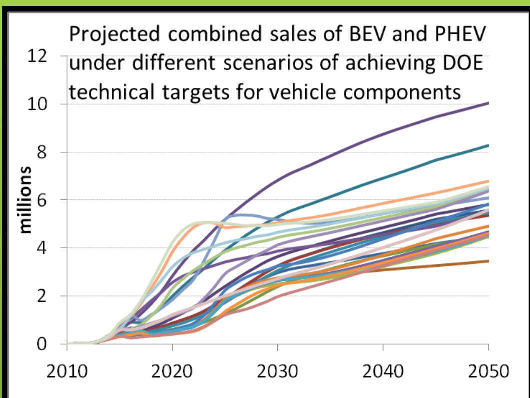
Cost-Analysis for AMPED Technologies

- Automotive-specific cost considerations
  - Fleet standardization of components
  - Regulatory
  - Warranty
- Available resources
  - Cost-modeling tutorial (ARPA-E)
  - Industry collaboration
  - National Labs and DOE VTP
    - **Argonne National Lab (ANL)**
    - **DOE Vehicle Technologies Program (VTP)**
    - **National Renewable Energy Lab (NREL)**
    - **Oak Ridge National Lab (ORNL)**

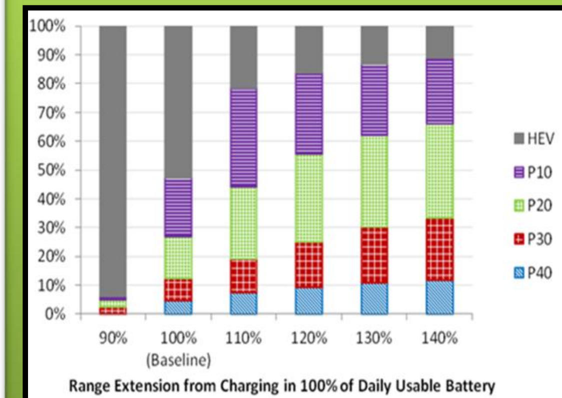
ORNL xEV Modeling Tools

ORNL has expertise in modeling the interactions between technology, infrastructure, behavior, policy and market.

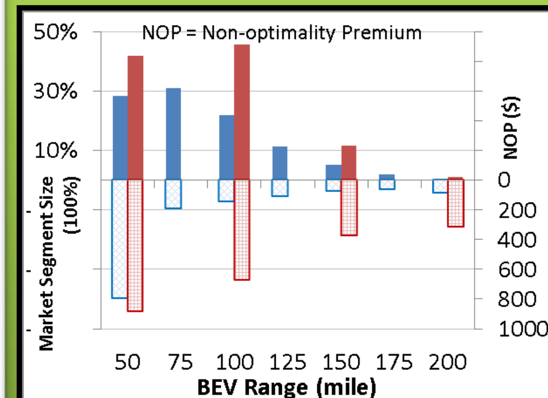
MA3T-- estimate demand for PEV by 1458 consumer segments



MOR-PHEV- Optimize PHEV e-range for U.S. drivers



MOR-BEV- Optimize BEV range for U.S. drivers

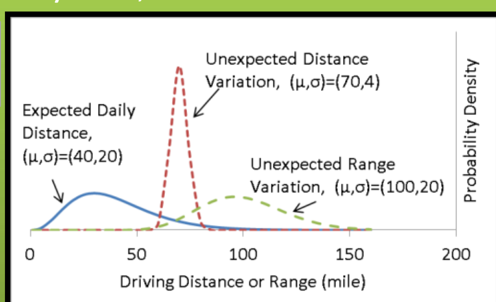


SED-- Quantify value of electric range and its sensitivity to charging infrastructure, range certainty, distance certainty, battery cost, value of time

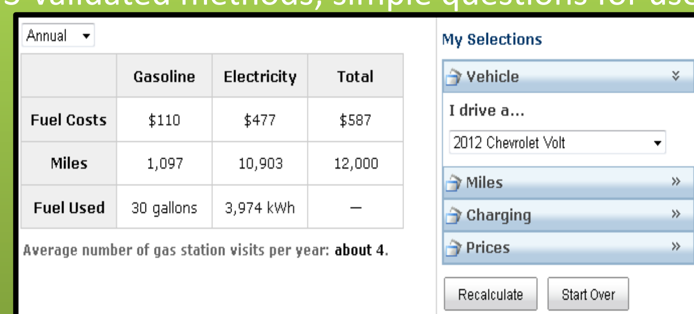
$$S = 365 S_0 \int_{R_e}^{+\infty} f(x_e)\,dx_e$$

$$E = 365 E_0 P_{ed} P_e$$

$$D = 365 D_0 P_{ed} (1 - P_e)$$



PHEV Calculator-- Estimate PHEV energy costs for individually-customized travel patterns; based on GPS-validated methods; simple questions for users



Annual

	Gasoline	Electricity	Total
Fuel Costs	$110	$477	$587
Miles	1,097	10,903	12,000
Fuel Used	30 gallons	3,974 kWh	—

Average number of gas station visits per year: **about 4.**

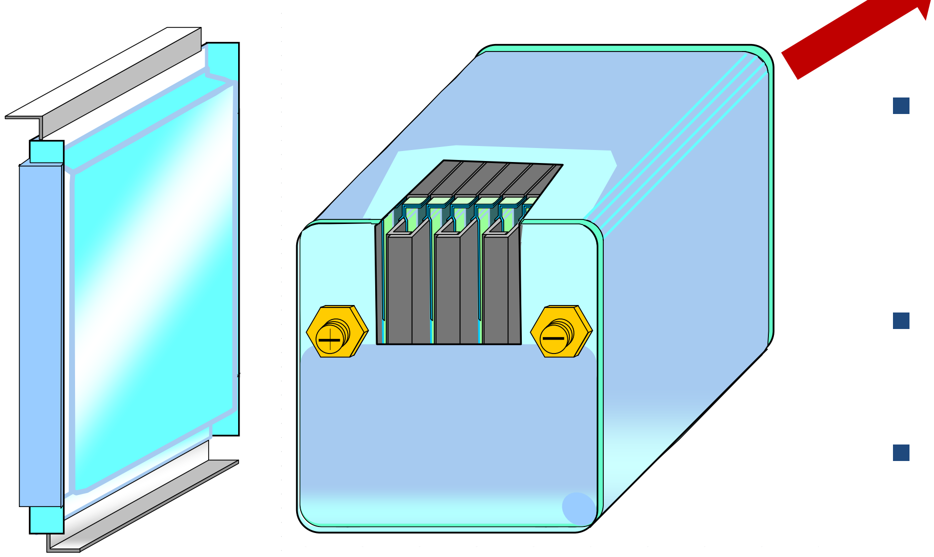
Summary of ORNL Areas of Expertise

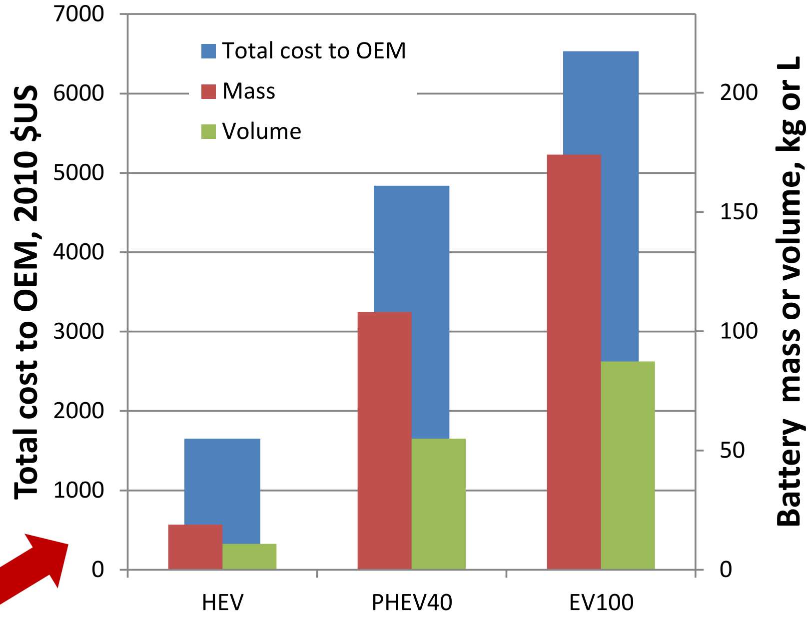
Applications of ORNL analytical tools generate insights about drivers and barriers of the PEV market, at both system and component levels.

- PEV value and travel pattern characterization
  - Lin, Z., Dong, J., Liu, C., & Greene, D. (2012). Estimation of Energy Use by Plug-In Hybrid Electric Vehicles: Validating Gamma Distribution for Representing Random Daily Driving Distance. *Transportation Research Record, 2287*(1), 37-43.
  - Lin, Z., & Greene, D. (2011). Predicting Individual Fuel Economy. *SAE International Journal of Fuels and Lubricants, 4*(1), 84-95.
  - Lin, Z., & Greene, D. L. (2011). Assessing Energy Impact of Plug-In Hybrid Electric Vehicles: Significance of Daily Distance Variation over Time and Among Drivers. *Transportation Research Record, 2252*(1), 99-106.
- Optimal vehicle design and consumer preferences
  - Lin, Z. (2012). Optimizing and Diversifying the Electric Range of Plug-in Hybrid Electric Vehicles for U.S. Drivers. *International Journal of Alternative Powertrains, 1*(1), 108-194.
  - Lin, Z. (2012). *Battery Electric Vehicles: Range Optimization and Diversification for U.S. Drivers.* Paper presented at the 91st Transportatin Research Board Annual Meeting, Washington, DC.
- Charging infrastructure—needs and impacts
  - Dong, J., & Lin, Z. (2012). Within-day recharge of plug-in hybrid electric vehicles: Energy impact of public charging infrastructure. *Transportation Research Part D: Transport and Environment, 17*(5), 405-412.
  - Lin, Z., & Greene, D. L. (2011). Promoting the Market for Plug-In Hybrid and Battery Electric Vehicles: Role of Recharge Availability. *Transportation Research Record, 2252*(1), 49-56.
- Integrated analysis of PEV market and societal value
  - Lin, Z., & Greene, D. (2010). *A Plug-in Hybrid Consumer Choice Model with Detailed Market Segmentation.* Paper presented at the The 89th Annual Meeting of Transportation Research Board, Washington, DC, January 10-14, 2010.
  - (Working) Impacts of DOE technical targets on EV's demand and environmental impacts
  - (Working) Sensitivities of EV demand to consumer preferences, energy prices, and range value

Modeling Li-ion Battery Performance and Cost: BatPaC

- Modeling real-world battery packs from bench-scale data
  - Prediction year 2020
  - Total cost of battery pack
  - Mass and volumes
- Battery is designed based on pack requirements and cell chemistry performance





- BatPaC model used by U.S. EPA and DOT for 2017-2025 light duty vehicle rule making
- Support from DOE EERE VTP: Dave Howell, Peter Faguy, and Tien Duong
- Available free-of-charge from www.cse.anl.gov

Modeling Li-ion Battery Performance and Cost: BatPaC

- BatPaC is based in Microsoft Excel® and may be modified to meet individual users' needs
- Existing BatPaC capabilities includes six Li-ion chemistries, liquid and air thermal management options, uncertainty calculation, etc

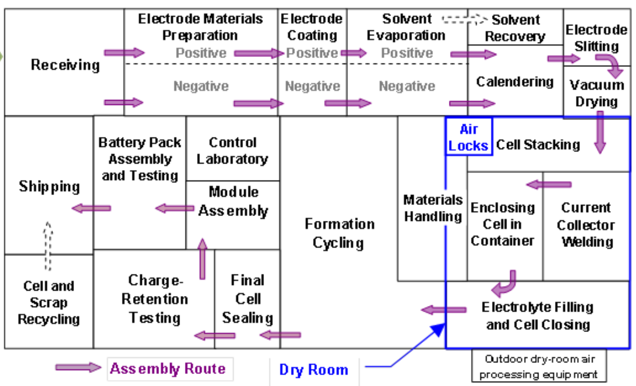
Iterate Over Governing Eqs. & Key Design Constraints

- Cell, module, & pack format
- Maximum electrode thickness
- Fraction of OCV at rated power

Battery Pack Components

- Volume
- Mass
- Materials
- Heat generation

$$\text{Process cost} = \text{Baseline cost} \cdot \left(\frac{\text{Processing rate}}{\text{Baseline processing rate}}\right)^{p}$$



- **Pack specifications**
  - Power and energy (range)
  - Number of cells
- **Cell Chemistry**
  - Area-specific impedance (ASI)
  - Reversible capacity C/3
  - OCV as function of SOC
  - Physical properties

Governing Equations

$$E = N \cdot C \cdot \left(U_E - \frac{C}{3}\frac{ASI_E}{A}\right)$$

$$L = \frac{C}{Q \cdot \rho \cdot \varepsilon \cdot A}$$

$$I = \frac{P}{A \cdot N \cdot U_P \left[\frac{V}{U}\right]}$$

$$A = \frac{ASI_P \cdot P}{N \cdot (U_P)^2 \left[\frac{V}{U}\right]\left(1 - \left[\frac{V}{U}\right]\right)}$$

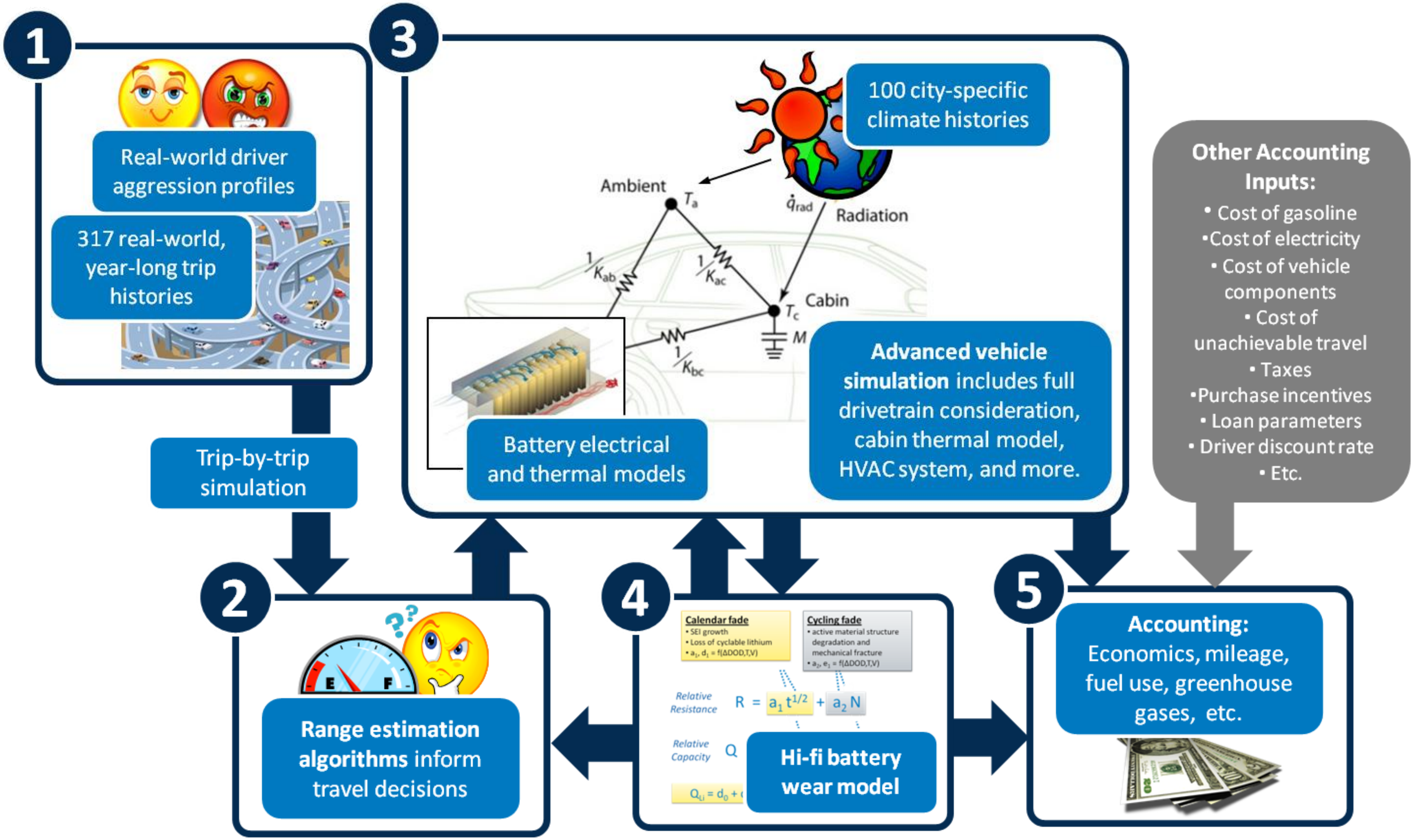
$$ASI = \frac{\alpha + f(I)}{L} + \beta$$

Total Cost to OEM

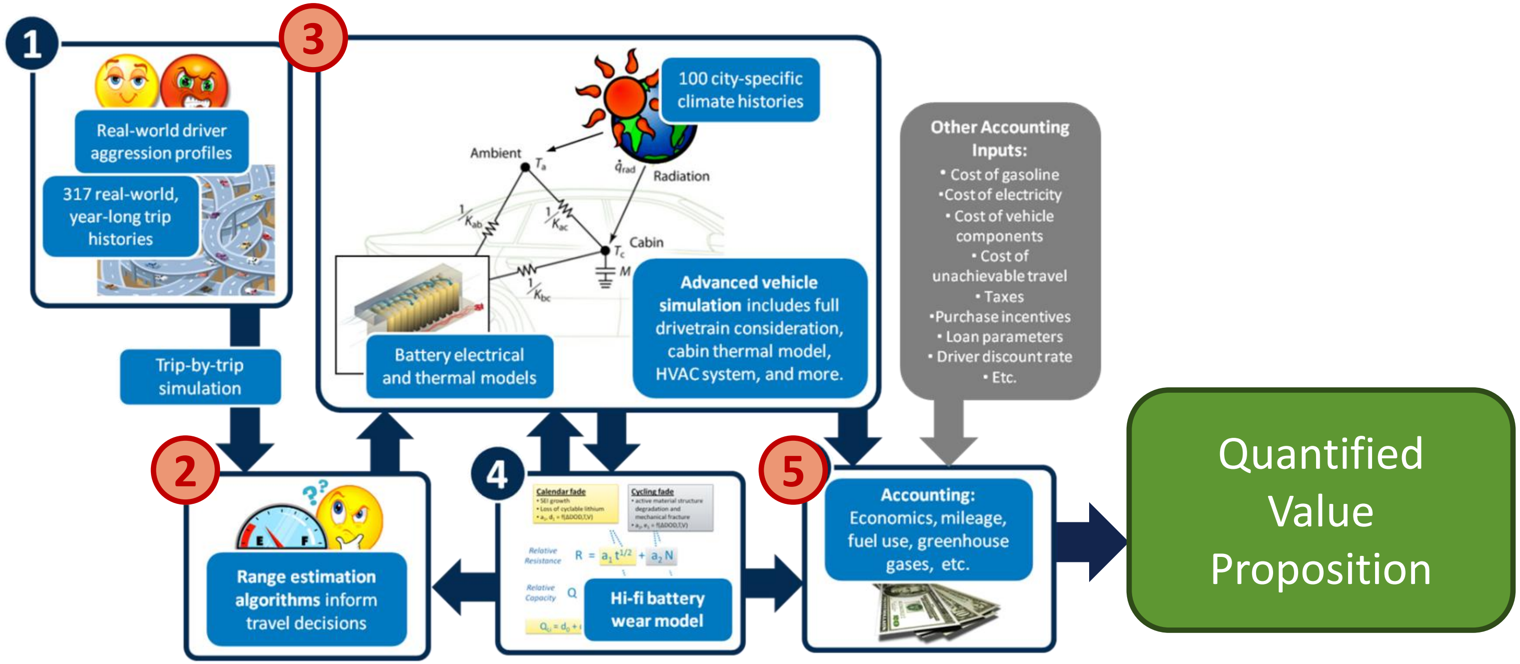
- Materials & purchased items
- Individual process steps
- Overhead, depreciation, etc.
- Warranty

NREL’s Battery Ownership Model (BOM)

- **Objective:** Perform accurate techno-economic assessments of HEV, PHEV, and BEV technologies and operational strategies to optimize consumer cost-benefit ratios



How the BOM can help AMPED teams



- **If your technology can...**
  - Decrease battery cost
  - Increase accessible battery capacity
  - Reduce battery wear
  - Improve SOC or SOH estimation
  - Improve battery efficiency
  - Reduce thermal management needs
  - Etc.
- **...then the BOM can quantify it's value**

- **AMPED team technology inputs:**
  - Up-front component costs (5)
  - Technology performance; e.g. SOC identification algorithms, battery controls strategies, state measurement accuracy, etc. (3)
  - Range estimation algorithms (2)
- **BOM outputs:**
  - OEM costs
  - Consumer costs
  - Consumer benefits

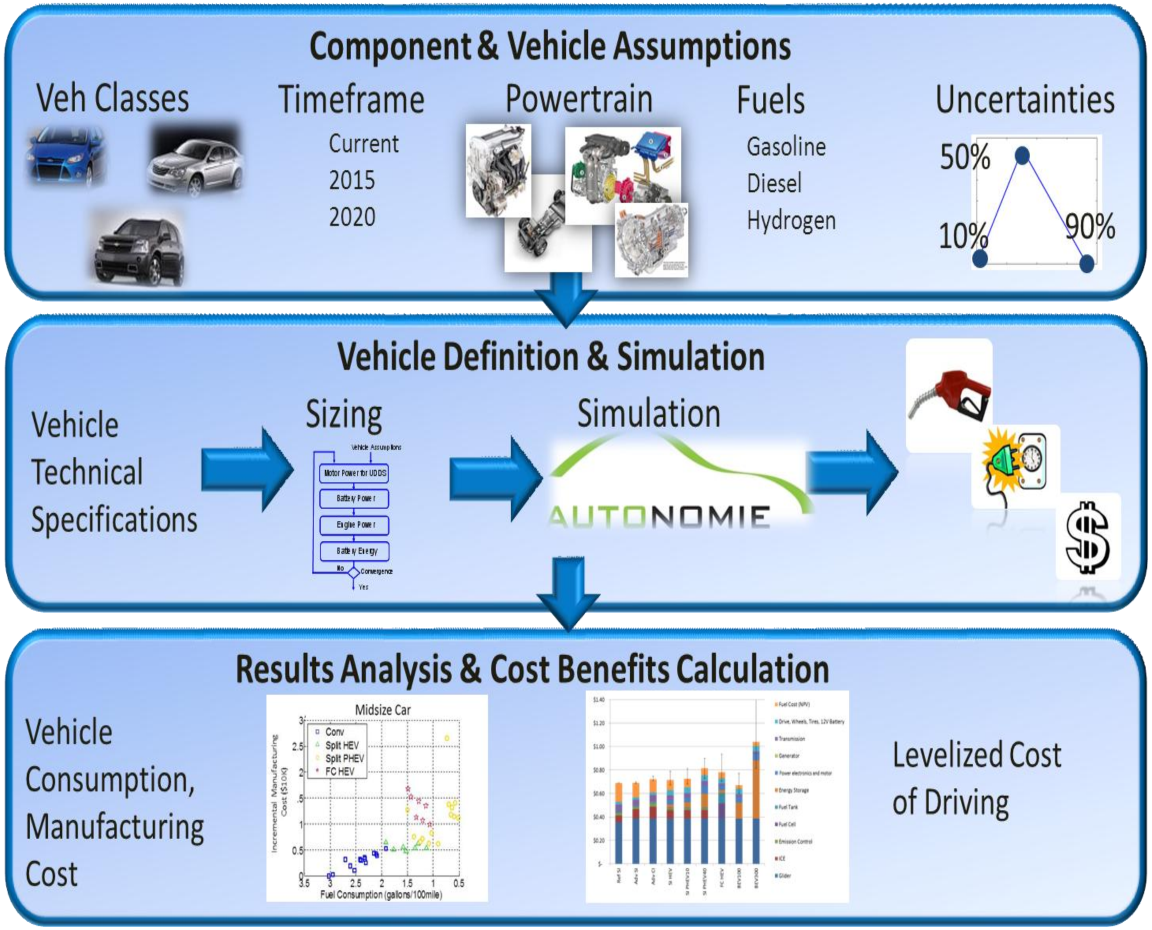
EV Everywhere Analysis Process Flow,

in three steps…

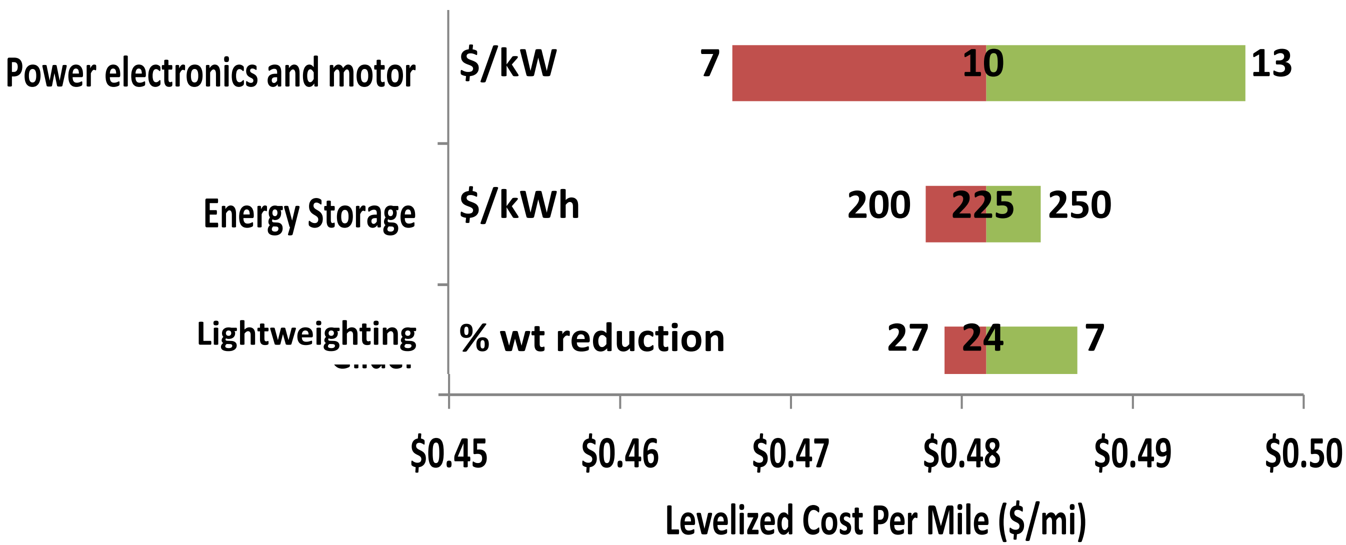
1. DOE experts **define the bounds of technical possibility** for technology key metrics
   - 90% “low progress” scenario
   - 50% “mid case” scenario
   - 10% “high progress” scenario

2. **Define virtual vehicles** in Argonne National Lab’s *Autonomie* modeling and simulation software

3. **Compare vehicles in a 5-year simple payback framework** within bounds defined by experts



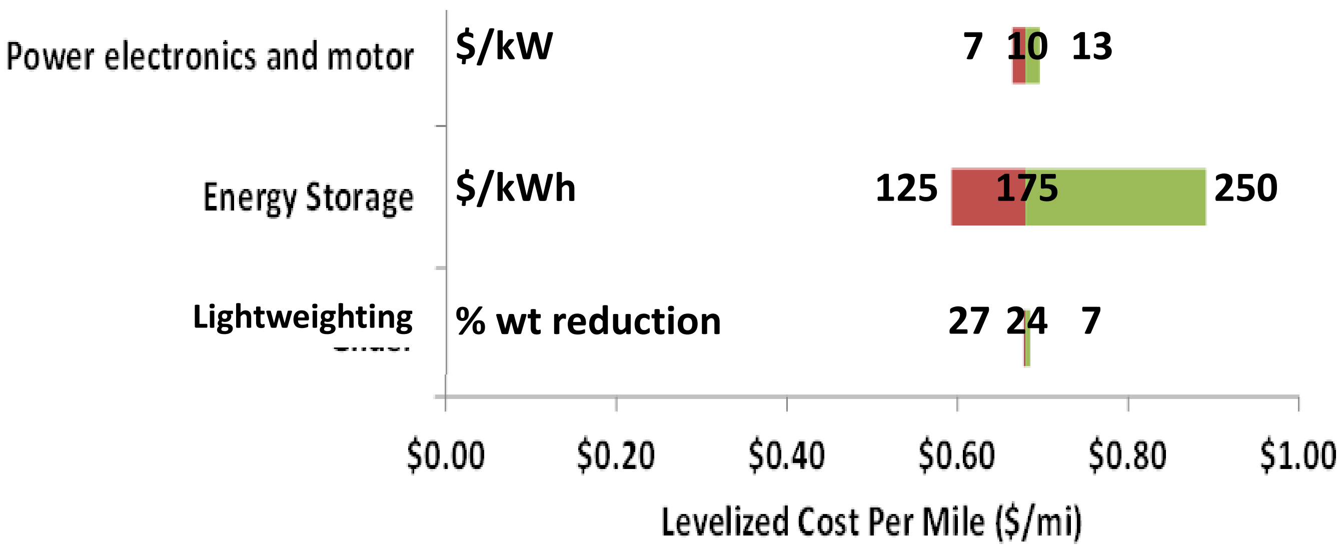
Analysis: 2022 Midsize SI PHEV40



$/kW	5
$/kWh	190
% wt	29

LCD-implied targets

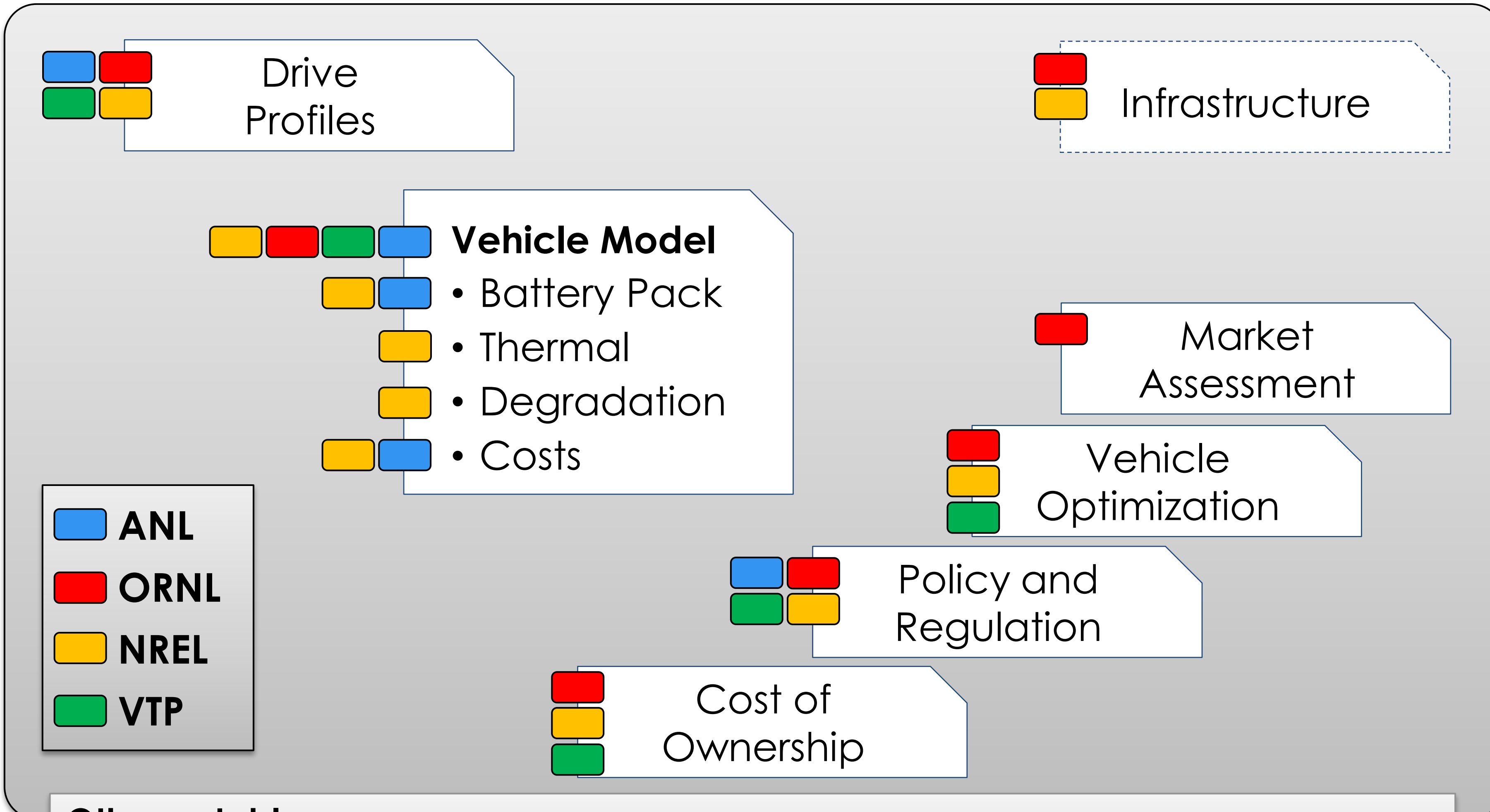
Analysis: 2022 Midsize AEV300



$/kW	4
$/kWh	110
% wt	30

LCD-implied targets

Landscape of xEV Resources from the DOE



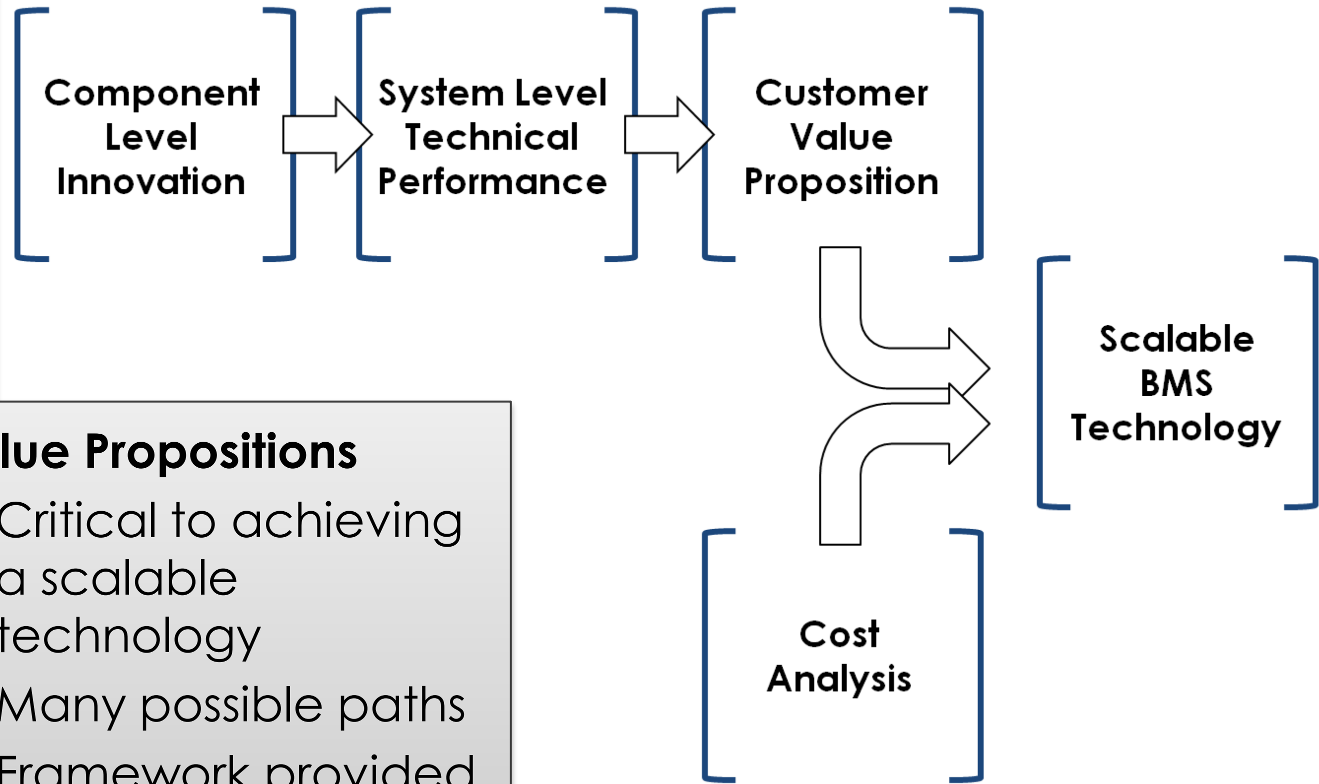
Other notable groups:

UC Davis - Market studies

MIT - Lightweighting, Vehicle adoption

What other resources are we missing?

Developing Scalable BMS Technologies



System Improvements

- Difficult finding the right information
- Difficult choosing the right system
- Leverage industry expertise and existing models

Value Propositions

- Critical to achieving a scalable technology
- Many possible paths
- Framework provided for quantifying and tracking value propositions

Cost Analysis

- Phased approach
- Leverage existing resources

Acknowledgments

- ARPA-E
  - Ilan Gur
  - Russ Ross
  - Amul Tevar
  - Tech-to-Market Team
- DOE VTP group
- National Labs
- Many industry collaborators

Questions and Discussion

Industry

- How much system performance improvement is needed to get your attention?
- What does it take for you to believe research cost projections?
- What are the key components of an effective pitch?

Research

- What other modeling resources are available?
- What industry information is most needed in the research community?

General

- What other trends will influence new BMS technologies?
- How will regulations affect value propositions and/or cost modeling?
- What scale-up pitfalls do automotive technologies fall into?